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MAGNETIC RESONANCE IMAGING METHODS AND COMPOSITIONS

The present application claims the benefit of U.S. provisional application number 60/260,524 filed January 10, 2001, which is incorporated by referenced in its entirety.

Funding for the present invention was provided in part by the Government of the United States by virtue of a grant (HL 61695) by the National Institutes of Health. Accordingly, the Government of the United States has certain rights in this invention.

BACKGROUND

1. Field of the invention.

The present invention relates to methods of magnetic resonance imaging (MRI), including use of new contrast agents. Methods and compositions of the invention are especially useful for imaging of cardiac tissue and, in particular, to the use of a paramagnetic contrast agent to decrease contrast and thereby allowing delineation between blood cavities (i.e., atrial and ventricular) and viable cardiac tissue, and non-viable, infarcted cardiac tissue.

2. Background of the invention.

Certain intravascular contrast agents have been used in proton (^{1}H) magnetic resonance imaging (MRI) of the cardiovascular system. In addition, certain iron oxide particles have been reported for use as MRI contrast agents for imaging the liver and spleen.

Sodium (^{23}Na) magnetic resonance imaging (MRI) has been used to detect signal elevations associated with nonviable myocardium after acute infarction and reperfusion. ^{23}Na MRI is uniquely capable of detecting altered sodium levels associated with impaired sodium-potassium pump function and nonviable tissue after acute infarction and reperfusion. Clinical applications of ^{23}Na MRI, however, are limited by the low in vivo

concentrations and NMR sensitivity of endogenous sodium, which translates to coarse spatial resolution and lower sensitivity compared to the ^{1}H MRI. ^{39}K MRI imaging suffers some similar problems. See, generally, U.S. Patents 5,910,112 and 6,205,349.

In the heart, the problem of low spatial resolution of ^{23}Na MRI images is further compromised by the high sodium content of ventricular blood which hinders differentiation of the ventricular wall from the ventricular cavity, and hence the differentiation of elevated sodium in myocardial infarction (MI). Thus, there tends to be minimal contrast between the ventricular cavity and infarcted cardiac tissue.

Several alternate ^{1}H MRI solutions could be adopted to overcome the inability to differentiate between the ventricular wall and the ventricular cavity due to the high sodium content of ventricular blood in ^{23}Na MRI. Such methods include black-blood ^{1}H MRI gradient echo and various spin dephasing imaging techniques. While these methods can attenuate ventricular sodium blood signals, these methods are associated with increased echo times (TE) or the need for cardiac gating, leading to detrimental signal-to-noise ratio (SNR) losses and significant prolongation of the total image acquisition times. Longer TE times lead to increased susceptibility induced artifacts and decreased SNR values in ^{23}Na images.

An additional disadvantage with these existing ^{1}H MRI imaging methods is that the close proximity of the longitudinal (T_1), fast ($T_{2,}$) and slow (T_{2f}) sodium transverse relaxation times of blood and myocardium preclude the use of conventional inversion recovery or spin-echo techniques to attenuate or null ventricular blood signals.

It thus would be desirable to have new methods for assessing biological tissue. It would be particularly desirable to have new methods for assessing cardiac tissue, especially through ^{23}Na or ^{39}K imaging techniques.

SUMMARY OF THE INVENTION

We have now discovered new methods and compositions for magnetic resonance imaging of biological tissue, particularly methods and compositions for ^{23}Na and ^{39}K magnetic resonance imaging of cardiac tissue.

More particularly, methods of the invention include use of an iron oxide contrast imaging agent in a variety of magnetic resonance imaging applications, particularly ^{23}Na and ^{39}K imaging of cardiac and other biological tissue. Preferred contrast agents for use in accordance with the invention comprise an iron atom coordinated with an organic polymer that has oxygen substitution, e.g. a polysaccharide such as a dextran.

Particularly preferred methods of the invention using an intravascular paramagnetic contrast agent to reduce or null sodium blood signals and to decrease the contrast between blood in the ventricular cavities and myocardial infarction using ^{23}Na MRI.

Preferred contrast agents of the invention comprise one or more iron atoms present in a complex, particularly complexed with one or more polymeric compounds. Oxygen-containing polymers are typically preferred, such as polysaccharides, particularly a dextran.

A particularly preferred intravascular paramagnetic contrast agent for use in accordance with the invention may comprise superparamagnetic intravascular iron oxide, T_2-relaxant contrast agent, MION-46. Optionally, the quantity of MION-46 introduced and the echo time (TE) are selected to minimize signal intensity differences between ventricular cavity blood and well-perfused viable myocardium; maximize signal intensity differences between non-viable myocardium and ventricular cavity blood in myocardial infarction; and maximize signal intensity differences between non-viable myocardium and well-perfused viable myocardium in myocardial infarction.

The invention, in one form thereof, is a method of ^{23}Na magnetic resonance imaging (MRI) of cardiac tissue for attenuating ventricular cavity blood signals and signals from viable perfused myocardial tissue and for visualizing non-invasively myocardial infarction. The method comprises introducing an intravascular paramagnetic contrast agent to attenuate the ^{23}Na MRI signal for ventricular cavity blood and viable well-perfused tissue. The cardiac tissue is then imaged using ^{23}Na MRI.

In yet a further embodiment, the method further comprises selecting a quantity of the MION-46 to be introduced and an echo time or imaging the cardiac tissue to minimize signal intensity differences between ventricular cavity blood and viable well-perfused myocardial tissue; maximize signal intensity differences between nonviable myocardium and ventricular cavity blood in myocardial infarction; and maximize signal intensity differences between non-viable myocardium and well-perfused viable myocardium in myocardial infarction.

The invention, in another form thereof, is a method for detecting myocardial infarction in cardiac tissue using ^{23}Na MRI comprising selecting a quantity of an intravascular paramagnetic contrast agent to be introduced and an echo time for imaging the cardiac tissue to minimize signal intensity differences between ventricular cavity blood and well-perfused viable myocardium; maximize signal intensity differences between non-viable myocardium and ventricular cavity blood in myocardial infarction; and maximize signal intensity differences between non-viable myocardium and well-perfused viable myocardium in myocardial infarction. The intravascular paramagnetic contrast agent is introduced to thereby attenuate ventricular cavity blood signals and viable well-perfused tissue. Next, the cardiac tissue is imaged using ^{23}Na MRI.

The invention, in yet another form thereof, is a method for detecting myocardial infarction in cardiac tissue comprising selecting a quantity of an intervascular paramagnetic contrast agent to be introduced and an echo time for imaging the cardiac tissue to minimize signal intensity differences between the ventricular cavity blood and viable well-perfused myocardium. The intravascular paramagnetic contrast agent is introduced to thereby attenuate

ventricular cavity blood signals and ^{23}Na MRI signals from viable well-perfused tissue. Next, the cardiac tissue is imaged using ^{23}Na MRI.

The invention also includes evaluation of MION-46, an intravascular superparamagnetic contrast agent as a sodium MRI transverse (T_2) relaxant in an effort to attenuate the intense sodium blood signal from the ventricular cavity and for enhancing the ^{23}Na MRI contrast in MI.

The invention also provides methods and compositions to visualize cardiac tissue to detect myocardial infarction by using an intravascular paramagnetic contrast agent to attenuate a sodium blood signal in ^{23}Na MRI.

The invention further provides methods and compositions to decrease the contrast of the ventricular muscle wall and ventricular cavity blood in myocardial infarction using ^{23}Na MRI.

The invention also provides methods and compositions to select an appropriate dose of the paramagnetic contrast agent to decrease the contrast between the ventricular cavity blood and viable well-perfused tissue, thereby delineating myocardial infarction, using ^{23}Na magnetic resonance imaging (MRI).

The invention still further provides methods and compositions to select an echo time (TE) in ^{23}Na magnetic resonance imaging which uses a paramagnetic contrast agent, to minimize signal intensity differences between ventricular cavity blood and well-perfused viable myocardium; maximize signal intensity differences between non-viable myocardium and ventricular cavity blood in myocardial infarction; and maximize signal intensity differences between non-viable myocardium and well-perfused viable myocardium in myocardial infarction.

The invention yet further provides methods and compositions to select a dose of paramagnetic intravascular contrast agent and an echo time to decrease the signal intensity differences between ventricular cavity blood and viable well-perfused cardiac tissue while maximizing the signal intensity differences between non-viable myocardium and ventricular cavity blood in myocardial infarction and maximizing signal intensity differences between non-viable myocardium and well-perfused viable myocardium and non-viable myocardium in myocardial infarction.

Subjects that may be identified or diagnosed in accordance with the invention include mammals, particularly primates especially humans, that may be suffering from, suffered from or suspected of suffering from a disorder or injury associated with the heart, e.g. cardiac injury such as may be associated with heart failure, cardiogenic shock, cardiac ischemia, or a cardiovascular disease such any of a myocardial ischemic disorder, e.g. coronary artery disease, including angina pectoris and myocardial infarction.

Identification or diagnosis methods of the invention may suitably comprise administering an imaging effective amount of a contrast agent in accordance with the present invention and imaging targeted tissue of the subject with ^{23}Na or ^{39}K magnetic resonance, particularly by imaging cardiac tissue.

Other aspects of the invention are disclosed *infra*.

BRIEF DESCRIPTION OF THE DRAWING

Figure 1 illustratively depicts ^{23}Na MRI of a cross-section of an infracted heart without the administration of a contrast agent;

Figure 2 illustratively depicts ^{23}Na MRI of a cross-section of an infarcted heart after the administration of a contrast agent according to the present invention;

Figure 3 illustratively depicts ^{23}Na MRI of a cross-section of an infracted heart after administration of a contrast agent at the target dose and optimum echo time (TE);

Figure 4 is a flow diagram schematically depicting a method of ^{23}Na MRI of cardiac tissue using a contrast agent according to the present invention;

Figure 5 is a plot depicting normalized ^{23}Na MRI signal intensity variation with MION-46 volume at various echo times (TE);

Figure 6A is a plot of T_1 and Figure 6B is a plot T_2 vs. MION-46 volume;

Figures 7A-7E illustratively depict coronal of images of a gel-blood phantom;

Figure 8A illustratively depicts pre-contrast axial images from a normal heart at optimal echo time of 5 ms and Figure 8B illustratively depicts post-contrast axial images from a normal heart at target dose/optimal echo time of 5 ms;

Figure 9 is a plot depicting ^{23}Na MRI signal intensity variation of myocardial tissue and ventricular blood regions with different MION-46 volume doses *in vivo*; and

Figure 10A illustratively depicts pre-contrast ^{23}Na MRI images of an infarcted heart, Figures 10B-10C illustratively depict post-contrast ^{23}Na MRI images of an infarcted heart and Figure 10D illustratively depicts a TTC stained slice of the excised heart.

DETAILED DESCRIPTION OF THE INVENTION

As discussed above, we have now found new methods and compositions for magnetic resonance imaging of biological tissue, particularly methods and compositions for ^{23}Na and ^{39}K magnetic resonance imaging of cardiac tissue.

The exemplary disclosure which follows often is made with respect to preferred contrast agent of MION-46 and ^{23}Na imaging. However, it is understood that disclosure is exemplary only, and other embodiments are fully within the scope of the invention as

discussed herein, e.g. other contrast agents, magnetic resonance imaging other than ^{23}Na, and the like.

Referring now to the figures, Figure 1 depicts a ^{23}Na MRI of a cross-section of infracted heart 10. Infarcted heart 10 is used for exemplary purposes to illustrate convention of ^{23}Na MRI of a cardiac tissue. Infarcted heart 10 Includes right ventricular cavity 12, left ventricular cavity 14 and ventricular wall 16. Infarcted heart 10 includes nonviable, infarcted myocardium 18 associated with a myocardial infarction.

^{23}Na MRI signal elevations are associated with nonviable myocardium 18. The elevated signal is the result of acute infarction followed by reperfusion of blood. Stated more precisely, ^{23}Na MRI detects myocardial infarction through altered sodium levels associated with cardiac tissue impaired sodium-potassium pump function of non-viable tissue after acute infarction and reperfusion.

In addition to the infarcted myocardial tissue 18, ^{23}Na MRI produces an intense signal for ventricular blood present in ventricular cavities 12, 14. As a result, there is minimal signal intensity differences between the ^{23}Na MRI signal for the infarcted myocardial tissue 18 and the ventricular cavities 12, 14. The lack of signal intensity differences between infarcted myocardial tissue 18 and the ventricular cavities 12, 14 may hamper ^{23}Na MRI detection of infarcted myocardium tissue 18.

Figure 2 depicts infarcted heart 20 after the administration of an intravascular paramagnetic contrast agent. Optimally, the intravascular paramagnetic contrast agent comprises superparamagnetic iron oxide such as MION-46. One manufacturer of MION-46 is Advanced Magnetics Inc. of Cambridge, MA.

MION-46 has an average core size of 4-7 nm, and contains 27% iron by weight. MION-46 contains one central iron oxide crystal to which multiple dextran molecules are attached, increasing the diameter of the agent to about 17 nm. The MION-46 particles are

scavenged from the blood by the reticuloendothelial system, especially the kupffer cells of the liver and have a half-life in the blood of about 81 minutes.

The MION-46 produces a hypointense signal in the ventricular cavities 22, 24 due to the paramagnetic effect of MION-46. As such, there is a reduction in intensity of ^{23}Na MRI signal from ventricular cavities 22, 24 in the presence of MION-46 as compared with signal associated with ventricular cavities 12, 14 in the absence of MION-46 (see Figure 1).

The MION-46 may also produce a hypointense or slight reduction in ^{23}Na MRI signal corresponding to viable tissue in the ventricular wall 26. At high doses of MION-46, capillary blood may supply MION-46 at sufficient quantity to produce a reduction in ^{23}Na MRI signal for ventricular wall 26. The reduction in ^{23}Na MRI signal in the ventricular cavities 22, 24 results in enhanced signal intensity differences of non-viable infracted myocardial tissue 28. As a result, infarcted myocardial tissue 28 becomes more readily detected.

Referring now to Figure 3, when the MION-46 dose (i.e. target dose) and TE are optimized for minimize signal intensity differences between ventricular cavity blood and well-perfused viable myocardium; maximize signal intensity differences between non-viable myocardium and ventricular cavity blood in myocardial infarction; and maximize signal intensity differences between non-viable myocardium and well-perfused viable myocardium in myocardial infarction, there is a hypointense signal in both ventricular cavities 33, 34 and ventricular wall 36 and a hypointense signal for the non-viable infarcted myocardium 38. Consequently, the major ^{23}Na MRI signals correspond to the non-viable infarcted myocardium 38.

Referring now to Figure 4, method 400 comprises the use of an intravascular paramagnetic contrast agent to attenuate sodium blood signals and to enhance the signal intensity differences between infarcted cardiac tissue and ventricular cavity blood in

myocardial infarction using ^{23}Na MRI. A baseline ^{23}Na MRI is performed on the heart of a subject (step 405), particularly a mammal, such as a human patient.

An intravascular paramagnetic contrast agent is introduced intravenously to attenuate ^{23}Na MRI signals for ventricular cavity blood and viable well-perfused tissue (step 410). Optimally, the intravascular paramagnetic contrast agent comprises superparamagnetic iron oxide MION-46.

In order to maximize the contrast between the ventricular cavities 32, 34 and ventricular wall 36, and the non-viable infarcted myocardial tissue 38, an appropriate (i.e. target) dose of MION-46 is selected and the echo time (TE) is selectively chosen (step 420). It was discovered that minimum signal intensity differences between blood in the ventricular cavities 32, 34 and ventricular tissue 36, and maximum signal intensity differences between non-viable myocardium and ventricular cavity blood in myocardial infarction (MI); and maximum signal intensity differences between non-viable myocardium and well-perfused viable myocardium in myocardial infarction myocardial tissue 38 is realized by adjusting the MION-46 dosage and adjusting the echo time (TE) of ^{23}Na MRI.

Further, it is preferable that the MION-46 dose and TE are optimized based on signal-to-noise ratio (SNR) loss, susceptibility induced loss and blood signal attenuation. When the MION-46 dosage and the echo time are appropriately selected, there may be a reduction in blood pool signal of about 61%.

Next, ^{23}Na MRI is performed on the heart of one who has had MION-46 administered intravenously (step 430). The intravenously administered MION-46 reduces the blood signal intensity in sodium images (i.e., ^{23}Na MRI).

One possible explanation for the decrease in blood signal intensity may be due to the modification of the short and long transverse relaxation time components of sodium. The MION-46 dextran particles are T_2-relaxants causing decrease contrast between blood and ventricular muscle, by decreasing the ^{23}Na signal from blood plasma. As a result of the blood

signal intensity suppression of the blood plasma signal, there is a reduction in ^{23}Na signal corresponding to the blood in the ventricular cavities 32, 34. Thus, ^{23}Na MRI after the intravenous administration of MION-46 provides decreased signal intensity differences between the ventricular cavities 32, 34 and the ventricular wall 36 (Figure 3) as compared with ^{23}Na MRI without administration of MION-46 where there is minimal signal difference between the ventricular cavities 12, 14 and the ventricular wall 16 (Figure 1).

In addition to suppressing the blood signal associated with the ventricular cavities 32, 34, MION-46 also reduces the signal observed from the ventricular wall 36 due to blood perfusion of the ventricular wall 36 by the intravenously administered MION-46. The hypointense ^{23}Na signal for ventricular wall 36 and a more substantial hypointense signal of the blood signal in the ventricular cavities 32, 34, due to MION-46 administration, produces a ^{23}Na MRI image with a maximum visualization of the non-viable infarcted myocardial tissue 28 with a minimal signal associated with ventricular cavities 32, 34 and ventricular wall 36. Consequently, post-contrast imaging using optimal MION-46 doses and echo times (TE) produces distinct delineation of the myocardial infarction 38.

While the present invention was described showing the enhanced contrast between the ventricular cavities 22, 24, and infarcted myocardium 28, similar enhancements in contrast may be realized between atrial cavities and nonviable infarcted myocardium.

The use of a paramagnetic intravascular contrast agent such as MION-46 may have potential additional uses in addition to providing enhanced contrast in myocardial infarction detection in ^{23}Na MRI. A contrast agent may be used for assessment of myocardial blood perfusion volume at rest and after following a vasodilatory stimulus response.

A contrast agent may be administered to a subject may any of a number of routes. Intravenous administration is a preferred administration route. After the contrast agent has

been administered, it is generally preferred to delay several minutes before imaging for the administered agent to reside in imaging effective amounts in cardiac tissue. Other administration routes also will be suitable, including direct injection into coronary tissue. A variety of subjects will be suitable for diagnosis and treatment in accordance with the invention, and typically are mammals, including primates, especially humans.

Optimal dosage amounts for any particular contrast agent and subject can be readily determined empirically. That is, the agent can be administered to the subject and the subject evaluated.

All documents mentioned herein are incorporated herein by reference. The following non-limiting example is illustrative of the invention.

EXAMPLE

Experiments were performed and data were collected employing the present method in a canine model of myocardial infarction. Specifically, the experiments were directed to evaluating variation in the blood T_1 and T_2 relaxation times with increasing MION-46 amounts and determining the optimal dose for contrast-enhanced ^{23}Na cardiac MRI in normal canine hearts *in vivo*.

All MRI studies were performed with a commercially available 1.5T MRI system (Signa, Horizon, Echo Speed, 5.7 Epic platform, GE Medical Systems, Milwaukee, WI) equipped with broadband spectroscopy capabilities, using a 16-pole quadrature ^{23}Na birdcage coil tuned to 16.89 MHz and interfaced with a quadrature hybrid splitter. ^{23}Na MRI was performed with a three-dimensional (3D) twisted projection imaging (TPI) sequence using conventional scanner hardware with gradient having a maximum amplitude of 2.2 mT/m, a maximum slew rate of 12 mT/cm/s, and with a slew rate duty cycle limit of 20%. The k-space traversals traced the surfaces of concentric cones contained inside a sphere of radius k_{max}. The desired gradient waveforms were computed from the k-space traversals and were used to encode the free induction decay.

In vitro studies were performed with a co-axial cylindrical plexiglass phantom of outer diameter 12 cm, and inner diameter 5 cm. A saline gel was prepared by mixing 4% per wt. of agarose into 500 ml of 65 mM saline in doubly de-ionized water, doped with 10mM of copper sulphate ($CuSO_4$) and poured into the outer annular compartment of the phantom. This agarose gel provides a reasonable approximation to the ^{23}Na MRI relaxation properties of myocardial tissue. Whole blood samples were prepared by adding heparin (with 8.6 mg of sodium per ml of heparin solution) to canine blood with predetermined amounts of MION-46, and placed in the inner cylindrical chamber of the phantom.

Conditioned mongrel dogs weighing 25-30 kg were sedated with 10 mg/kg ketamine, 2.4 mg/kg xylanine, and 0.02 mg/kg atropine intramuscularly. An intravenous catheter was introduced, and the dog anesthetized with sodium penthothal, intubated, mechanically ventilated with 100% oxygen (tidal volume =10-15 ml/kg, respiratory rate = 10-12 bpm) and maintained on general anesthesia with 1-2% isoflurane. Three dogs were studied as normal controls. Three dogs were subjected to a 90 to 120-minute balloon occlusion of the left anterior descending (LAD) coronaxy artery followed by reperfusion. A femoral artery cutdown was performed to place a 8 Fr. catheter introducer sheath (Terumo Medical Corp., Elkton, MD) and a 7 Fr. right Judkins catheter (Cordis, Diamond Bar, CA) with a 0.014 mm guidewire and 3.5 Fr. coronary angioplasty balloon into the left anterior descending coronary artery under fluoroscopic guidance. The balloon was deflated and the occluder removed to allow reperfusion 3 to 6 hours prior to the MRI studies. MION-46 (42 mg Fe/ml, Advanced Magnetics Inc., Cambridge, MA) was injected intravenously in normal and in infarcted animals prior to contrast MRI. After MRI, infarcted dogs were humanely euthanized and the heart excised, sliced along the axial planes, and incubated in triphenyl-tetrazolium chloride (TTC) to identify viable from non-viable myocardium.

Dogs were positioned in the magnet in right decubitus, and an ECG-gated multislice gradient echo-transaxial ^{1}H MRI was performed with a flexible, 4-element phased array coil after autoshimming. The ^{1}H phased-array coil was then replaced by the ^{23}Na birdcage coil without repositioning the animal. The ^{23}Na three-dimensional twisted

projection imaging (3D) (TPI) sequence was applied with TE=0.37 ms, TR=60 ms, 14 NEX, and a receiver bandwidth of 31.25 kHz, 1240 projections and gradient strengths up to 0.16 G/cm. To maximize detection of the short T_2 component, a 0.4 ms non-selective 90° radio frequency (rf) excitation pulse was used. Post-contrast ^{23}Na MRI was performed (TE=0.37 ms, 5ms) at increasing MION-46 doses in normal dogs, and in infarcted animals at the target dose level of 10 mg/kg body weight (as determined from the normal dog experiments) to produce the greatest suppression of ventricular blood. The scan time per acquisition was approximately 17 minutes.

To determine the variation of the ^{23}Na relaxation times of blood with the amount of MION-46 injected, T_1 and T_2 measurements were carried out using saturation recovery (TR=60-300 ms) and spin-echo spectroscopic sequences (TE=12-35 ms) at increasing MION amounts ranging from 0-0.25 ml. The acquisition parameters were; 8-32 kHz, 256-512 points, NEX=96. T_{2f} and T_{2s} and image contrast were also measured from sequentially acquired ^{23}Na TPI images with TE=0.37-17 ms, TR=55 ms, NEX=4, in 4 min. of scan time per acquisition.

Magnetic resonance spectroscopy (MRS) data from the phantom experiments were processed for peak area measurements. Selected peaks from blood spectra were fitted in the frequency domain by fitting Lorentzian or Gaussian functions and the areas computed by integration. Raw TPI data were reconstructed off-line on a Silicon Graphics (SGI) workstation using a regridding algorithm and 3D Fourier transformation.

To determine the T_{2f}, T_{2s} and image signal intensity as a function of MION-46 amount, mean signal intensities were measured in multiple regions of interest (ROI) in sequentially acquired phantom and heart images (reconstructed at different TE values that ranged from 0.37-20 ms) with software developed previously. T_{2f} and T_2 values were determined by fitting image intensities (measured over 20-30 voxels within selected ROIs) and peak spectral areas as a function of TE to double exponential curves using a nonlinear least squares procedure based on the Marquardt-Levenberg algorithm (Multifit, Version 2.0, Day Computing, Cambridge, UK).

Figure 5 depicts the ^{23}Na signal intensity normalized by the pre-contrast intensity of isolated canine blood (approximately 80 ml) as a function of MION-46 quantity (0 - 0.25 ml of 42 mg/ml of MION-46) and TE in the two compartment gel-blood cylindrical phantom. The MION-46 was mixed with blood to ensure a homogeneous distribution in the compartment. ^{23}Na MRI performed at TE values of 0.37 - 5 ms showed larger decreases in normalized blood signal intensity at long echo times and larger MION-46 volumes, reaching a 65% decrease at TE=5 ms for an administered MION-46 volume of 0.25 ml. Although the signal intensity decreased monotonically with increasing MION-46 volumes and longer TE values, signal-to-noise (SNR) and susceptibility induced losses also increased.

Figure 6 shows the sodium T_1, T_{2f}, and T_{2s} in the isolated blood phantom as a function of MION-46 volume in isolated, heparinized blood at 37°C. Maximum effect on both T_1 and T_2 is observed at larger values, although MION-46 volumes exceeding about 100 µl do not elicit further significant reductions in relaxation times. MION-46 administration in isolated blood caused a T_1 decrease from 30 ms (no MION-46) to 23 ms with 0.25 ml of MION-46. The fractional T_2 reductions were more prominent (Fig. 6B) With T_{2f} changing from 6.2 ms (no MION-46) to 2.3 ms with 0.1 ml of MION-46, and T_{2s} from 16.4 ms to 6 ms with 0.25 ml of MION-46.

A series of coronal images from the gel-phantom is shown in Figure 7. Fig. 7A shows an image of the gel phantom without blood at TE=0.37 ms, whereas Fig. 7B and Fig, 7C show images at TE=0.37 ms and at TE=5 ms, respectively, with blood added but no MION-46. Fig. 7D shows an image of the same phantom at TE=5 ms at a MION-46 volume of 0.25 ml. The blood signal intensity is almost completely eliminated. On the other hand, the same phantom with the same MION-46 value imaged at TE=0.37 -ms reveals the blood-filled inner compartment (Fig. 7E). In general, SNR values in blood and gel regions of the phantom ranged from 10 - 24. Contrast-to-noise ratio (CNR) decreased from 9.3 (no MION-46) to -11.5 at the administered MION-46 volume of 0.25ml. T_1 and T_2 measurements from gel regions of the phantom were found to be 30.3 ms and 38.4 ms, respectively.

Typical pre- and post-contrast axial images from a normal dog heart are shown in Figure 8. The contrast between the ventricular blood and normal (i.e. viable well-perfused) myocardium decreased with larger MION-46 doses as shown in Fig. 9. A dose of 10 mg/kg bw was chosen as optimal, since the image quality was compromised at higher doses by susceptibility-induced losses (Fig. 7B). Imaging at such a dose translated to a mean 61% decrease in blood signal decrease in the ventricular cavity in the normal dogs. Signal decrease was also evident in the liver. Pre- and post-contrast images at TE of 0.37 ms and 5 ms and dose values of 10 mg/kg of MION-46 in an infarcted dog heart are shown in Fig. 10. Administration of MION-46 resulted in signal dropout in all myocardial areas except the anterior wall (Fig. 10C) which corresponds to the infarcted or TTC-negative region (Fig. 10D). In this animal, the CNR between the infarct and the ventricular blood pool in sodium images was 11.2 pre-contrast, compared to -25.2 post-contrast, representing an 325% contrast improvement.

Based on the experiments performed and data collected, the following conclusions were made. Blood plasma is a major contributor to the sodium signal in cardiac ^{23}Na MRI. The administration of MION-46 to the blood pool reduces both the T_1 and T_2 relaxation times in ^{23}Na MRI. Based on the data presented here, the mechanism of action is believed to be due to susceptibility induced reductions of the fast and slow transverse relaxation components. The results from both in vitro and in vivo blood experiments demonstrate the importance of choice of both the echo time, and MION-46 concentration in optimizing the reduction in blood ^{23}Na signal decrease. The phantom experiments with isolated blood showed that the best strategy for maximum reduction in blood signal intensity is to adjust TE to eliminate the T_{2s} signal component, as demonstrated in Figure 6. Almost complete elimination of the blood signal is observed after administration of MION-46 volume of 0.25 ml in approximately 80 ml of blood in images acquired with TE=5 ms compared to those acquired at a TE of 0.37 ms, consistent with the fact that both the T_{2f} and T_{2s} were reduced to 6.5 ms or less at this MION-46 volume.

The contrast between the myocardial wall and ventricular blood was decreased from about 4-fold to 2-fold with MION-46 administration at a dose of 10 mg Fe/kg body weight. Dose and TE choices were optimized based on SNR, susceptibility induced losses and blood signal attenuation. Since susceptibility induced artifacts are also tissue/organ geometry dependent, becoming worse at longer TE values, attention was paid to orient the short axis of the heart with the external magnetic field and to choose the minimum possible TE to attain maximum contrast. Note that the myocardial signal is reduced by approximately 25% at larger doses, possibly due to the expected 10-15% of blood volume signal in the myocardial capillary bed that may be completely or partially eliminated by the contrast agent. It remains to be determined whether the intravascular sodium affected by MION-46 administration, is due to fast exchange of sodium across blood vessel walls or extension of the large susceptibility gradients into the extravascular space.

Macromolecular MRI contrast agents may have toxic effects. No adverse toxic reactions have been observed in this study for the range of the injected doses administered (0-17 mg Fe/kg body weight); there were no changes in heart rate, blood pressure or anesthetic depth.

These experiments provide support for the use of the contrast agent MION-46 for enhancing the detection of myocardial infarction in vivo by ^{23}Na MRI and for the utility of the using MION-46 to diagnose heart disease.

These experiments provide support for the practical use of the contrast agent for clinical applications in ischemic heart disease. Although the agent caused large reductions in the signal intensity in the ventricular blood and smaller reductions in normal myocardium, it allowed the clear differentiation of non-viable infarcted tissue. Use of MION-46 may provide a useful method for enhancing the noninvasive identification of the location and extent of myocardial infarction by ^{23}Na MRI. Its applications and use might be extended to the study of myocardial perfusion at rest and after a vasodilation stimulus for the evaluation of isehemic disease. Furthermore, since the drug distribution depends on particle size, it will be important in future

studies of myocardial infarction to relate the volume of distribution of the drug to the area of ^{23}Na image enhancement to assess the extent of the injury.

Although the invention has been described above in relation to preferred embodiments thereof, it will be understood by those skilled in the art that variations and modifications can be effected in these preferred embodiments without departing from the scope and spirit of the invention.